Background of the Invention

The present invention relates to imaging through a random medium such as the turbulent atmosphere or the slowly changing optics of a camera and how to combat the deleterious effects of that medium, in real-time and automatically by means of an adaptive optics system.

US patent 4,309,602 entitled "Wavefront Sensing by Phase Retrieval" describes the use of adaptive optics including an image signal processor to provide a wavefront error signal representative of estimated wavefront distortion. A control system responds to the wavefront error signal to reduce phase distortion.

Other relevant US patents are as follows: 3,979,585, "Adaptive Imaging Telescope with Camera-Computer Transform Image Quality Sensing and Electro-Optic Phase Shifting"; 3,923,400, "Real-time Wavefront Correction System."; 4,141,652 "Sensor System for Detecting Wavefront Distortion in a Return Beam of Light"; 5,166,508, "Optical Processor for Controlling a Deformable Mirror"; 5,350,911."Wavefront Error Estimation Derived from Observation of Arbitrary Unknown Extended Scenes"; 5,384,455, "Measurement-Diverse Imaging"; 5,412,200 "Wide Field Distortion-Compensating Imaging System and Methods"; and 6,107,617,"Liquid

Crystal Active Optics Correction for Large Space Based Optical Systems".

The following publications describe various prior approaches required to deal with the effects of adverse atmospheric conditions on optical functions.

1. R. W. Gerchberg and W. O. Saxon, "Phase Determination from Image and Diffraction Plane Pictures", Optic, 34, 275 (1971).
2. R. Gonsalves, "Phase Retrieval from Modulus Data", J. Opt. Soc. of Am, 66, 961 (1976).
3. J. Fienup, "Phase Retrieval Algorithms: a Comparison," Ap. Opt., 21, 2758 (1982).
4. R. Gonsalves, "Phase Retrieval and Diversity in Adaptive Optics", Opt. Eng., 21, 829 (1982).
5. B. Ellerbroek and D. Morrison, "Linear Methods in Phase Retrieval," SPIE Proc. 351, 90 (1982).
6. M. Teague, "Deterministic Phase Retrieval: a Green's Function Solution," J. Opt. Soc. of Am, 73, 1434 (1983).
7. R. Gonsalves, "Phase Retrieval by Differential Intensity Measurements", J. Opt. Soc. of Am A, 4, 166 (1987).
8. R. Paxman and J. Fienup, "Optical Misalignment Sensing and Image Reconstruction Using Phase Diversity," J. Opt. Soc. of America, A 5, 914 (1988).
9. F. Roddier et al., "A Simple Low-Order Adaptive Optics System For Near-Infrared Applications", Publications of the Astronomical Society of the Pacific, 103, 131 (1991).
10. J. E. Graves et al., "The University of Hawaii Adaptive Optics System: III "The Wavefront Curvature Sensor", SPIE Proc., 1542, 262 (1991).
11. R. Kendrick, D. Acton, A. Duncan, "Phase-Diversity Wave-

12. M. A. Voronstov and V. P. Sivokon, " Stochastic Parallel-Gradient-Descent Technique for High-Resolution Wave-Front Phase-Distortion Correction," J. Opt. Soc. Am. A, 15, 2745 (1988).

Most known adaptive optics systems use a wavefront sensor, which provides an estimate of the distorting wavefront. Wavefront sensing is done by any of the five following mechanisms.

1. Dithering. This method continuously changes the adaptive optic and monitors the image quality of the observed image. This method applies slowly varying changes to each channel of the adaptive optic, modulates each channel, demodulates the image quality in each channel, and controls the adaptive optic with the set of image qualities. One example of this approach is found in the aforementioned paper entitled " Stochastic parallel-gradient-descent technique for high-resolution wave-front phase-distortion correction".
2. Shearing Interferometer. This method uses a reference beam to create an interference pattern, which describes the unknown wavefront and requires a laser-based interferometer.
3. Shack-Hartmann Sensor. This device uses an array of lenses and a sensor image to focus small sections of the wavefront onto a detector. Shifts in the small images are caused by local tilts in the waveform, which allows the wavefront to be reconstructed. .
4. Curvature Sensing. This arrangement uses two or more images, measured along the path of the optical system. The local curvature of the propagating wave is determined and it is propagated, by computer simulation, back to the aperture. The computer-generated phase controls an adaptive optic in the method shown within the aforementioned publications,

5. Phase retrieval and diversity. This arrangement employs digital imagery, an adaptive optic, and multiple images as described within the aforementioned US patent 4,309,602 entitled "Wavefront Sensing by Phase Retrieval".

In the most relevant prior art devices, the diversity is a quadratic phase shift, which can be introduced by defocusing the optical system and recording, simultaneously, both the in-focus image and the defocused image thereby requiring additional optical equipment.

Accordingly, it would be advantageous to provide the diversity utilizing successive frames of a video recording of the object, without requiring any such additional optical equipment.

Summary of the Invention

The invention describes the use of diversity imaging for determining the aberrations caused by the medium and how to control an adaptive optic in the optical system to eliminate the aberrations. Diversity imaging uses one or more of the images, each with a known diversity such as phase, wavelength, or spatial shift, to deduce both the unknown object and the parameters of the medium. Sequential frames of a video recording of the object herein provide the diversity. The sequential frames are the diversity images and a sequential processor is employed to control the adaptive optic.

BRIEF DESCRIPTION OF THE DRAWINGS:

Figure 1 is a diagrammatic representation of the imaging system, which uses an adaptive optic and a sequential diversity processor, in accordance with the invention;

Figure 2 is a flow chart representation of the algorithm used within the sequential diversity processor of Figure 1; and Figures 3A-C depict a computer simulation of the imaging of a point source viewed through a turbulent atmosphere and the corresponding point source when diversity imaging is used to reduce the effects of turbulence, in accordance with the invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

As shown in Figure 1, the sequential diversity imaging system 12 receives an optical signal 1 which may have aberrations introduced by a randomly changing medium. The optical signal passes through an aperture 2 and is imaged by a lens 3. Between lens 3 and detector 5 is an Adaptive Optic 4, hereinafter, "AO." The detector 5 is an array of photodiodes, not shown, each of which provides a signal of magnitude related to the intensity of radiant energy incident thereon, as described in the aforementioned US patent 4,309,602.The adaptive optic may comprise a matrix of controllable reflecting surfaces which can be controlled to vary the delay of incident radiant energy so as to reduce the wavefront error signal as also described in the recently-noted US patent. The output of detector 5 is a video sequence of digital images, as indicated at 6. This sequence of images is the input to a Sequential Diversity Processor 7. The processor produces control signals 8 which control the configuration of the AO, so as to cancel the aberrations introduced by the random medium. The AO is a high-resolution device, which allows a wide range of correction mechanisms, such as Zernike polynomial fitting of a

currently installed on national telescopes and has capabilities well beyond the automatic focusing and registration mechanisms in consumer camcorders. Such an AO is capable of improving image quality by about a factor of ten.

Figure 2 shows a flow diagram depicting the image flow through the lens 3, AO 4, detector 5 and the processing of data within the Sequential Diversity Processor 7 of Figure 1. The k^{th} frame of the video output, 6, is named I(k). It is an input to the Diversity Algorithm 10. Other inputs to the Diversity Algorithm 10 are successively delayed versions of I(k), namely I(k-1), I(k-2), ..., which are delayed and stored in a digital buffer such as the Delays 9A-C in Figure 2.
The k^{th} output of the Diversity Algorithm is D(k) and delayed versions of it, are used as inputs to a Predicted Algorithm 11 which predicts the change in the random medium for the next frame of the video sequence and controls the AO 4 with a control signal T(k)as indicated at 8. The other inputs to the Prediction Algorithm 11 are delayed versions of the control signal T(k).
To further describe the flow diagram of Figure 2, we adopt the following, notation and assume that the media aberration is due to an unknown wavefront distortion, which is typical of atmospheric distortion.

Referring to Fig. 1 and Fig. 2, we use the following notation:

W(k)- Unknown distorting wavefront at time k.

T(k) = Phase put on the AO at time k.

C(k) = Compensated phase to be estimated by a

I(k) = Measured image at time k.

D(k) = Diversity phase.

We consider a diversity algorithm where I(k-1) is the first image and I(k) is the diversity image. With this convention the diversity phase is the change in the AO phase from time k-1 to time k. Thus,

$$D(k) = T(k) - T(k-1) \quad (2)$$

The phase diversity algorithm is set up to estimate C(k), the compensated phase at time k. Call the estimate Q(k). Q(k) is, from equation (1),

$$Q(k) = W1(k) + T(k), \qquad (3)$$

where W1(k) is an estimate of W(k), the unknown phase at time k. (We know T(k), so it need not be estimated.) At time k + 1 we would like to set the AO phase to the negative of the unknown wavefront at time k+1. We do not know W at time k+1 but we do have an estimate of the wavefront at time k, namely, W1(k). This will be a good estimate of W(k+1) if AO updates are well within the time constant of the changing medium. Thus, we set

$$T(k+1) = -W1(k), \qquad (4)$$

which will tend to cancel the wavefront distortion at k+1.

Solving (3) for W1(k) and substituting it into (4), we have

$$T(k+1) = -Q(k) + T(k),$$

which implies

$$T(k) = -Q(k-1) + T(k-1). \quad (5)$$

Turning to the diversity phase, we put (5) into (2) to get

$$D(k) = (-Q(k-1) + T(k-1)) - T(k-1) = -Q(k-1) \quad (6)$$

This is the specification for the diversity phase at time k.

Finally, we put (6) into (5) to get a new expression for the AO phase:

$$T(k) = T(k-1) + D(k). \quad (7)$$

Equations (6) and (7) give us the recipe we sought. The AO phase, T(k), is the previous AO phase plus the diversity phase, D(k); and the diversity phase is the negative of the diversity algorithm's output at time k-1.
These equations are expressed in block diagram form in Fig. 2. The inputs to the diversity algorithm are images I(k-1) and I(k); the output is Q(k), an estimate of the compensated phase; the phase diversity is D(k); and a feedback loop calculates T(k).

Figures 3A-3C show a computer simulation of 24 cycles of the sequential diversity imager. The object is a point source, such as a star. The first pairs of observed images of the star are shown in Fig 3A wherein the compensated images are directly above the

observed images are shown in Figure 3B and the third pairs of observed images are shown in Figure 3C. The lower rows in each Figure show how the star "twinkles" over time. Each uncompensated image is called a speckle pattern and is characteristic of a star imaged through the earth's atmosphere.

A measure of the image quality is the Strehl ratio, i. e., the peak value of the aberrated star image to the peak value of an unabberated star image. Higher Strehl ratio means higher image quality. For the 24 images shown, the average Strehl ratio is 0.045.

The sequential diversity imaging technique produced the images shown directly above each twinkling image. The average Strehl ratio for the compensated images is 0.467. This is an improvement of about a factor of 10.

We note that in our simulation the time constant of the atmospheric disturbance is about eight images; that is, the star image takes about eight cycles to appear completely uncorrelated with its earlier image. Thus the cycle time of the imager is, in this simulation, eight times shorter than the time cycle of the atmosphere. The latter is quite variable, but a reasonable estimate is 8 milliseconds. Thus, the sequential processor must measure the new image and calculate the new AO settings in about one millisecond.

When we doubled the atmospheric time constant to 16 ms, the average Strehl ratio of the imager improved to 0.65, an increase of about 14 in the image quality, over the uncompensated star images. When we halved the atmospheric time constant to 4 ms, the average Strehl ratio improved only to 0.29, an increase in image quality of a factor of about 6.

Finally, we allowed the atmospheric time constant to vary from 2 to 16 ms over the 24-image sequence and the average quality factor